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Coulomb interaction of quasi-2D magnetoplasmons

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Abstract. Tunneling is a powerfull tool of the determination of one-electron structure of 2D systems. Recently a strong interaction of cyclotron and intersubband tunneling resonanses was observed in the case when the one-particle Landau levels of different 2D subbands do not interact. In this connection the long-wave structure of quasi-2D magnetoplasmons is calculated for the actual system of two quasi-2D layers divided by a barrier in a perpendicular magnetic field. It is shown that the Coulomb interaction of inter- and intrasubband magnetoplasmons is able to lead to their strong anticrossing. Magnetoplasmon-assisted tunneling processes will reveal themselves as anticrossing Landau levels of different 2D subbands.

Investigations of the tunneling between quasi-two-dimensional electron systems based on (001) GaAs/$Al_{0.4}Ga_{0.6}As$/GaAs in a magnetic field parallel to the current revealed a strong interaction between Landau levels of different two-dimensional subbands in GaAs which was observed as an anticrossing of the related peak positions in the tunnel current vs voltage curves as a function of magnetic field [1]. The splitting of the interacting Landau levels was of the order of 10 meV, which cannot be explained by nonparabolicity of the conduction band in GaAs. An alternative mechanism leading to the anticrossing is related to the emission of magnetoplasmons. Energy of an electron that has tunneled into the system with the completely discrete spectrum may relax by the emission of 2D magnetoplasmons (the emission of optical and acoustic phonons is forbiden in that case).

The aim of the paper is calculation of the magnetoplasmon spectrum in the above tunnel structure. The results published in the theoretical papers contain very rich resonance structure of the magnetoplasmon spectrum in several 2D systems, but the results depend very sensitively on the approximation used. Here it is shown that the Coulomb interaction of inter- and intrasubband magnetoplasmon branches leads to their strong anticrossing in qualitative agreement with the experimental data.

We consider a symmetric structure (001) GaAs/$Al_{0.4}Ga_{0.6}As$/GaAs with a single thick barrier in magnetic field $\mathbf{B}$ parallel to the growth axis Oz in the gauge of the vector potential $\mathbf{A} = (-By, 0, 0)$. The 2D electron gas (in (x, y) plane) occupy two accumulation layers (with the concentration of 2D electrons N_s in each) formed in GaAs close to both sides of the AlGaAs barrier. The single-particle electron states in both quasi-2D layers are considered independetly, so that, for instance, the states in the right-hand layer are described with the envelope function:

$$F_{nmk}(\mathbf{r}) = (2\pi)^{-1/2} f_n(z) \exp(ikx)\chi_{mk}(y), \tag{1}$$

and the proper self energy E_{nm}. Here n is the subband index, $f_n(z)$ is the z-motion function, m is the Landau level index, k is the wave number, and $\chi_{mk}(y)$ relates to the oscillator function. Following Ref. [2] we will consider the linear response of the system on the perturbation

$$\delta U = U(z) \exp(-i(qx + \omega t)). \tag{2}$$

In the random phase approximation after some algebra we will have the following equation for the perturbation ($\hbar = 1$):

$$\frac{d^2U(z)}{dz^2} - q^2U(z) = -\frac{2e^3B^2}{\epsilon c}\sum_{\substack{n,m\\ n',m'}}\frac{\left(f^0_{nm} - f^0_{n'm'}\right)A^2_{mm'}(q)U_{nn'}f_n(z)f_{n'}(z)}{E_{nm} - E_{n'm'} + \omega + i\delta}. \tag{3}$$

Here e is the electron charge, $\epsilon = const$ is the dielectric constant, c is the speed of light, $f^0_{n,m}$ is the Fermi function, $U_{nn'}$ is the matrix element of $U(z)$ on the functions of z-motion, and for $A_{mm'}(q)$ we have:

$$A_{mm'}(q) = \frac{eB}{c}\int_{-\infty}^{\infty}\chi_m(y)\,\chi_{m'}\left(y + \frac{cq}{eB}\right)dy. \tag{4}$$

As we are considering the electrons tunneling from the left-hand layer to the right-hand one, only anti-symmetric solutions of Eq. (3) we are interested in. So, the Green function of Eq. (3) is taken in the form

$$G(z,z') = \frac{1}{2q}\exp\left(-q\left|z + z'\right|\right) - \frac{1}{2q}\exp\left(-q\left|z - z'\right|\right), \tag{5}$$

where $z = 0$ is the coordinate of the middle of the barrier. Now Eq. (3) takes the matrix form:

$$U_{ll'} + \frac{e^3B}{\epsilon cq}\sum_{nn'}\mathcal{I}_{ll'nn'}\Pi_{nn'}U_{nn'} = 0. \tag{6}$$

where

$$\Pi_{nn'} = \sum_{mm'}\frac{\left(f^0_{nm} - f^0_{n'm'}\right)A^2_{mm'}(q)}{E_{nm} - E_{n'm'} + \omega + i\delta}, \tag{7}$$

and in the dipole approximation

$$\mathcal{I}_{ll'nn'} \approx q\int_0^{+\infty}\left(\left|z - z'\right| - (z + z')\right)f_n(z')f_{n'}(z')f_l(z)f_{l'}(z)dzdz'. \tag{8}$$

In the long-wave approximation we have non-zero $A_{mm'}$:

$$A^2_{mm} \approx 1; \qquad A^2_{mm-1} = A^2_{m-1m} \approx \frac{cq^2m}{2eB}. \tag{9}$$

We take into account only the ground and first excited subbands, energy separation between which is Δ. We will have a system of three linear equations (6), determinant of which defines the spectrum of magnetoplasmons. The final dispersion equation is:

$$\begin{aligned}&\left(\omega^2 - \omega_0^2\right)\left(\omega^2 - \omega_c^2\right)\left(\omega^2 - (\Delta + \omega_c)^2\right) - \gamma q^2\left(\omega^2 - \Delta^2\right)\left(\omega^2 - \omega_c^2\right)\\ &-\alpha q^2\left(\omega^2 - \omega_0^2\right)\left(\omega^2 - (\Delta + \omega_c)^2\right) - \beta q^2\left(\omega^2 - (\Delta + \omega_c)^2\right)\\ &+q^4\left(\omega^2 - \Delta^2\right)(\alpha\gamma - \rho) = 0,\end{aligned} \tag{10}$$

where

$$\alpha = \frac{e^2M_1 2\pi N_s}{m\epsilon}, \quad \beta = \frac{e^4M_2^2\Delta 8\pi^2N_s^2}{m\epsilon^2}, \quad \omega_0^2 = \Delta^2 + \frac{e^2M_3\Delta 4\pi N_s}{\epsilon},$$
$$\gamma = \frac{e^2M_3 2\pi N_s(\Delta + \omega_c)}{m\epsilon\omega_c}, \quad \rho = \frac{e^4M_2^2 4\pi^2N_s^2(\Delta + \omega_c)}{m^2\epsilon^2\omega_c}, \tag{11}$$

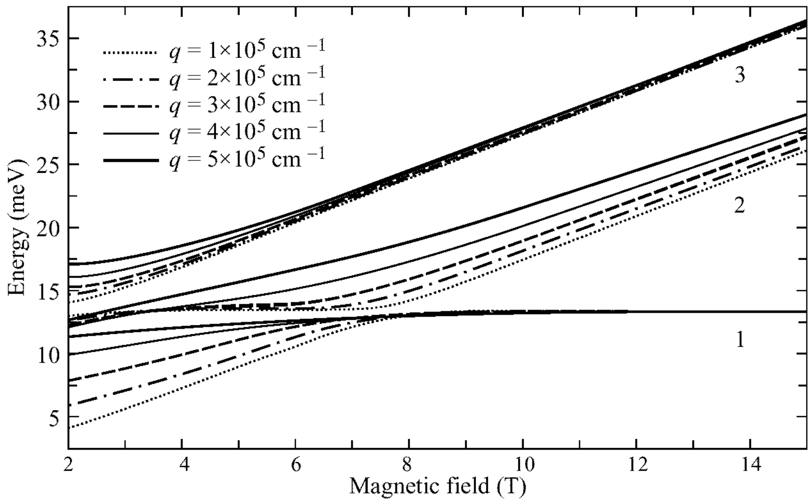

Fig. 1. Plasmon energy (three branches) vs magnetic field at various wave numbers. The branch #1 is the intrasubband plasmon, the one #2 is the intersubband plasmon, the last one #3 is the combination resonance plasmon.

m is the band edge electron effective mass, ω_c is the cyclotron energy, and the dipole matrix elements

$$M_1 = -q^{-1}\mathcal{I}_{1111} > 0, \quad M_2 = -q^{-1}\mathcal{I}_{1112}, \quad M_3 = -q^{-1}\mathcal{I}_{1212} > 0. \tag{12}$$

The result (10) may be understood as following: the intrasubband magnetoplasmons, intersubband ones and combined resonance ones mutually interact via the Coulomb energy.

The result may be presented on the plot 1. The dependence of the magnetoplasmon energy on the magnetic field at various wave numbers is shown. The performed self-consistent calculation yelds $M_1 = 270$ Å, $M_2 = 26.6$ Å, $M_3 = 20.7$ Å, and we take $N_s = 3 \times 10^{11}$ cm^{-2}. This plot demonstrates the above-mentioned effect of anticrossing. There are three magnetoplasmon branches: intrasubband branch 1, intersubband branch 2, and combined resonance branch 3, which appears due to the $(n = 0, N = 0)$ to $(n = 1, N = 1)$ transition, where n is the principal quantum number of the two-dimensional subband and N is the Landau level index. Only the anticrossing of branches 1 and 3 is resolved in the experiment. Magnetoplasmon-assisted tunneling processes can thus be revealed in this type of structure as an anticrossing effect in the resonances observed between different 2D subbands.

Acknowledgements

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